First GPS signals reflected from the interior of a tropical storm: Preliminary Results from Hurricane Michael

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Abstract

Using GPS signals reflected from the ocean surface is developing into a simple technique for measuring sea-state and inferring surface wind speeds. Theoretical models have been developed which are considered valid to approximately 24 meters per second. The GPS reflection technique has an obvious extension to extremely high sea states, cyclones and extra-tropical storms. In October of 2000 a GPS system mounted in a NOAA Hurricane Hunter research aircraft, was flown into Hurricane Michael off the South Carolina coast. The first acquisition of GPS signals reflected from the sea surface inside tropical cyclones was accomplished. This paper presents some examples of the data sets as well as early wind speed retrieval results using direct extensions of current models. Data from the GPS wind speed retrievals as well as from direct aircraft measurements are compared and discussed.

Introduction

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It has been demonstrated that reflected GPS signals are strong enough to provide the basis of a bistatic L-band scatterometer [1,2,3]. Many aircraft flights have been done at NASA's Langley Research Center to develop the phenomenology of the reflected GPS signal. These include TOPEX and QuickScat underpasses with over-flights of buoys separately or in conjunction with satellite overpasses. Comparison of various wind speed retrieval techniques using these flights has been done to determine calibration constants, accuracy and possibility of wind direction retrieval. The wind speeds encountered in these flights have varied from virtually calm to nearly 20 meters per second. Efforts have been underway to determine effective retrieval techniques, including non-linear estimation and matched filter methods. The basis for the retrievals is either integration of some wave spectrum model to determine mean-square slopes for a Gaussian probability density or by using the Cox and Munk[4], -Gram Charlier slope probability density. Existing models are understood to represent the wave spectrum or mean square slope dependence on wind speed up to around 24 meters per second. These wind speeds are those amenable to inter-comparison with some *in situ* data sources and generally would be representative of well-developed seas. Above 24 meters per second, there is virtually no literature available, as far as mean-square-slope dependence on windspeed, and very little experimental data either. The opportunity presented by Hurricane Michael to acquire GPS reflection data in high wind conditions was welcome as an important step in extending the phenomenology of the reflection technique.

Receiver installation and operation

The modified GPS receiver used in this installation is similar in operation to others[2] that have been developed by the NASA-Langley group. In effect, a GPS receiver is reorganized to have 'mother' channels and 'daughter' channels. The mother channels track the GPS satellites in normal fashion (including generating a position solution for convenient geo-referencing.) The daughter channels have their satellites, Doppler offsets, and pseudo-noise code starting points set for them by their mother channels. The daughter channels step their replica codes through a range of delays and the delays are reset. At each delay, the power received at that delay is recorded, and the process is cycled repeatedly until the data-take ends. The mother channels ensure that the daughters track the GPS satellites properly as far as code-starting point is concerned. Bulk range delay is removed (but recorded) by simple calculation of geometry.

As described in Katzberg and Garrison[5], the loci of constant delay form a family of range ellipses when projected onto the surface, which are nearly concentric for the altitudes and surface scattering generally encountered in practice. The receiver integrates the incoming, down-converted signal for one of the Coarse Acquisition (C/A) code cycles (one millisecond, to high accuracy), and then transfers the value to the host computer. The signal components are squared and added to give a measurement of power. The power so obtained represents weighted contributions of power from ±1 code chip. The peak weighting is at the range ellipse corresponding to the number of delay steps and decreases quadratically out to ±1 code chip. The interval between one commanded delay and the next is one-half code chip. These sample steps yield 'Nyquist-rate' samples in *power-versus-delay* to ensure the ability to reconstruct the form of this function.

Hurricane Michael

With the assistance of the NOAA-Environmental Technology Laboratory, Boulder CO and the NOAA Hurricane Research Division, Miami FL, permission was given to install the GPS receiver in one of the WP-3D Hurricane Hunters: N42RF 'Kermit.' The NASA-Langley Receiver was installed by members of the NOAA Airborne Operations Center at MacDill AFB and operated by them during flight. Installation was completed in late August 2000. The first data received was from the outer edges of Hurricane Keith taken October 1, 2000, followed by a data set from Hurricane Leslie on October 5, 2000. The emergence of Hurricane Michael presented the first opportunity to traverse the core of a tropical cyclone on October 18, 2000. Hurricane Michael (Tropical depression 17) formed in the Western Atlantic the evening of October16. It reached tropical storm strength the next morning and was classified a hurricane that same afternoon. Michael increased forward speed the night of October18. It sped northward, made landfall as a hurricane in Newfoundland on October 19, and quickly began losing tropical characteristics. At the time of the aircraft penetration, the storm was moving at approximately 35 knots. Figure 1 is a map derived from the GPS position information, which shows the aircraft flight path from MacDill, FL, into the center of Hurricane Michael and subsequent flying in and around storm. The cross represents the center of the storm (from Hurricane Research Division data) during the time the GPS surface reflection data were taken.

<u>Data acquisition details</u>

The aircraft flew out from the coast at about 5000 meters. It descended to approximately 1400 meters traversed the eye of the storm, and then descended further to around 500 meters where it stayed for the bulk of the time the GPS equipment was left on. On the return leg, the aircraft returned at an altitude of approximately 5000 meters, although only during a portion of this leg was reflected data recorded. A magnified section of the track is shown as an inset in Figure 1. As discussed above[5], the semi-major and semi-minor ellipses of constant delay increase as the square-root of the code offset in the receiver. The scattering angle, on the other hand, is fixed by the mean-square-slope of the surface irregularities. The GPS technique may be thought of as measuring the width of the internal receiver correlation function as it is affected by surface roughness. If the receiver altitude is too low, almost all the scattered power is captured in the area on the surface corresponding to the first few range bins, hence the width of the internal correlation function is difficult to determine. Even with hurricane force winds, 500 meters altitude would considerably limit the power outside the first range bin for the C/A code. Fortunately, the very first storm transect by the aircraft, shown in Figure 1, did include a run at about 1400 meters.

Characteristics of the Data

The GPS data were promptly received from the Airborne Operations and processing was started. The first data sets developed were the aircraft flight-path and a catalog of the GPS satellites tracked by the receiver. The receiver software keeps track of the available satellites via an almanac. As one satellite falls below a certain minimum elevation angle it is replaced by another. In this flight, sixteen satellites were tracked, but only GPS satellite PRN numbers 05, 21, 25, 29 and 30 were in view during the entire 1400-meter data-take. One or two others were briefly available, but were either too low or not visible during the entire storm core transect (PRN 23, for example.) Near the beginning or end of visibility for any GPS satellite, the angle can be too low to avoid interference from aircraft engines, other equipment, fuselage, etc. Moreover, the antenna being used is an LHCP patch and has poor response at very low elevation angles. There was some evidence this was occurring and data segments were bypassed in processing if it appeared the signal level was dropping below appropriate values for very low elevation angles. At the beginning of the transect satellite PRN 21 had the highest elevation (80 degrees and 201 degrees azimuth.) PRN 29 was next highest (57 degrees and 356 degrees azimuth), followed by PRN 30 (48 and 113 degrees), then by PRN 25 (38 degrees and 251 degrees.) Finally, PRN 05 was at 34 degrees elevation and 65 degrees azimuth.

The GPS signal is one that results from power reflected from wave facets which are properly oriented to redirect the satellite-to-earth ray-path to the nadir antenna on the aircraft. Since the delay bins map the surface, they generally cover all significant scattering angles. In this fashion, the slope probability density is "sampled" over all scattering angles. Thus, the total power in the reflected signal is of interest since it is an indicator of the surface reflection process. It is commonly seen at lower wind speeds that the total scattered power is close to that of the direct signal, reduced by the reflectivity of the water (approximately 63 percent.) The signal shape changes, but not the total power.

The receiver measures power by squaring the accumulated results of multiplying the incoming signal by the reference PRN code for a particular satellite. Both noise and signal are squared, resulting in a "noise floor" whose average value is (ideally) related to the thermal noise in the receiver front end. For this receiver, the noise floor is approximately 120,000 digital counts. Shown in Figure 2a are two samples of the power versus delay recorded from the receiver from satellite SV-08 (PRN 21.) If the noise floor is subtracted from the various sample bins and the resulting values are added, a result of 2,475,000 is obtained. Typical values for the direct signal are in the neighborhood of 3,200,000-4,000,000. The total received signal for PRN 21 in Hurricane Michael is thus seen to be similar to that found for much lower wind speeds and consistent with the expected reflectivity. The data for all the other satellites (except as noted above, for some very low elevation angles,) showed similar values. Thus the total reflected signal, even from the wind speeds of tropical storms, is very high and similar to the case of much lower wind speeds.

Preliminary wind speed retrievals

The development of wind speed retrieval techniques, as well as wind direction algorithms, is currently a subject of considerable effort. The wind speed retrievals have shown good success in providing accurate spatial mapping of surface winds in long-fetch-long-duration sea state conditions. The techniques being applied are non-linear mean square estimation and a matched filter approach[6]. Because the matched filter technique is relatively easy to implement, this technique can be used for "quick-look" retrievals. This approach was used to provide preliminary retrievals for presentation here in anticipation of more detailed analysis later.

Examples of the theoretical power versus delay are shown in Figure 2b for wind speeds of 1-meter per second (dashed line) and 23 meters per second (solid line.) The matched filter technique consists of generating a complete set of model "waveforms" from theory and sliding properly scaled and sampled versions of each against the recorded data. The maximum cross-correlation is found and the wind speed corresponding to this waveform is then assigned to the data. The next power versus delay reading is then processed in the same way until the data set is complete. Shown in Figures 2c and 2d are samples of the result of this process taken from the Michael data for satellite PRN 21. It is evident that the match is very good, which is commonly the case. Nevertheless, the technique tends to generate a wind speed even for very poor data. Data editing techniques will ultimately form part of operational wind speed algorithms, but have not yet been implemented. In addition, the model waveforms are based on the Cox and Munk Gram Charlier (with mean square slopes reduced to account for the GPS wavelength.) The case of a highly dynamic situation, such as the rapidly moving Hurricane Michael, has a double impact on the GPS technique: high wind speeds and an evolving sea state.

As a calibration check on the technique and data sets, retrievals were done over the entire time-in-view of a couple satellites. One segment of the flight path on the outbound leg is shown in Figure 1(b) with retrievals for PRN 29. Near the point at which the aircraft left the Florida coast is NOAA Canaveral Buoy (41009.) At the time the aircraft exited the coast this buoy reported an average wind speed 7.0 meters per second with sustained gusts to 9.0 meters per second (closest one hour report.) As can be seen from the figure, the retrieval is consistent with the buoy data. The full retrieval for PRN 29 is shown in Figure 3(a) from the coast to the area where the aircraft descended from approximately 5000 meters down to the 1450-meter level. This occurs in Figure 3(b) just west of –70.0 degrees. The eye of the storm is at approximately -69.78 degrees. All retrievals show a similar result of approximately 15-16 meters per second in a plateau, with non-noise peaks of well over 25 meters per second randomly alternating with valleys at or near the plateau level.

Comparison of GPS wind speed retrievals with other data

In order to determine whether the GPS reflection data utilizing the matched filter technique can "find" the eye of the storm, a data set was obtained from the NOAA Hurricane Research Division (HRD) with the "flight-level-wind-speed." This data is derived from the drift the aircraft experiences when flying into the storm. Initially the retrieved wind speed data was plotted for each satellite and compared with the HRD data. The high variability of the GPS retrievals made comparison difficult. The peak wind speeds appeared consistent with the HRD data, but the minimum winds in the "eye" were much too high. It seemed reasonable that the rapid movement of the storm to the northeast did not allow establishment of the mean square slopes characteristic for such winds. Certain areas of the storm might have been expected to show such slopes while others might not. Under this assumption, all the data were plotted together and then examined to see if the structure of the storm could be detected. For consistency with the HRD data, one-minute time averages were performed. This had the effect of eliminating some of the peak wind speeds retrieved. These higher values were sustained over several seconds and were believed, consequently, not to be the result of noise. Moreover, the multiple seconds and sparse time sampling done with this receiver implementation (a few samples per second data rate, averaged over a few seconds) ensured uncorrelated data samples from the sea surface. Shown in Figure 3(b) is the result of selecting the maximum, one-minute averaged retrieved wind speed from each of the satellites at a particular location plotted with the HRD flight level wind speed. The location of the eye is indicated by the two, 5-meter per second wind speeds near 32.5 degrees latitude.

The matched-filter, GPS-derived values are considerably below those from the aircraft drift data. The maximum, one-minute average for the GPS is approximately 23.5 meters per second, while the maximum for the HRD data is around 31 meters per second. Moreover, the minimum for HRD data is 5 meters per second, while the minimum for the GPS-derived data is down at the "plateau" level of near 15 meters per second. There appears to be a reasonable agreement between the overall shape of the GPS and HRD data.

Discussion and conclusions

This paper has presented some initial wind speed retrievals from the first GPS surface reflection data taken from inside a tropical storm. The data were found to indicate that the received signal power levels are relatively strong and comparable with those levels found at much lower wind speeds. The data sets would have to be considered marginal in signal-to-noise ratio and at very low altitudes for what is normal for these retrievals. Nevertheless, the data sets produced good agreement with the available buoy data off the Florida coast. Retrievals were presented that indicate significant under-estimates of wind speed, by as much as 8 meters per second. On the other hand, qualitative agreement with flight level derived wind speeds was obtained.

The retrievals must be considered as indicative of GPS-surface reflection performance and the matched filter retrieval approach in particular. Ocean wave spectra or mean-square-slope models are generally assumed to only have validity below 24 meters per second. The use of the lower wind speed, Gram Charlier probability density is probably open to considerable question. The very fast movement of Michael, indicating a highly dynamic situation (limited wave age, limited fetch) also would limit retrieval accuracy based upon mean-square-slopes. Nevertheless, the results found so far are encouraging and await collection of a database from various storm conditions to assess the ultimate capability of the GPS surface reflection technique.

<u>References</u>

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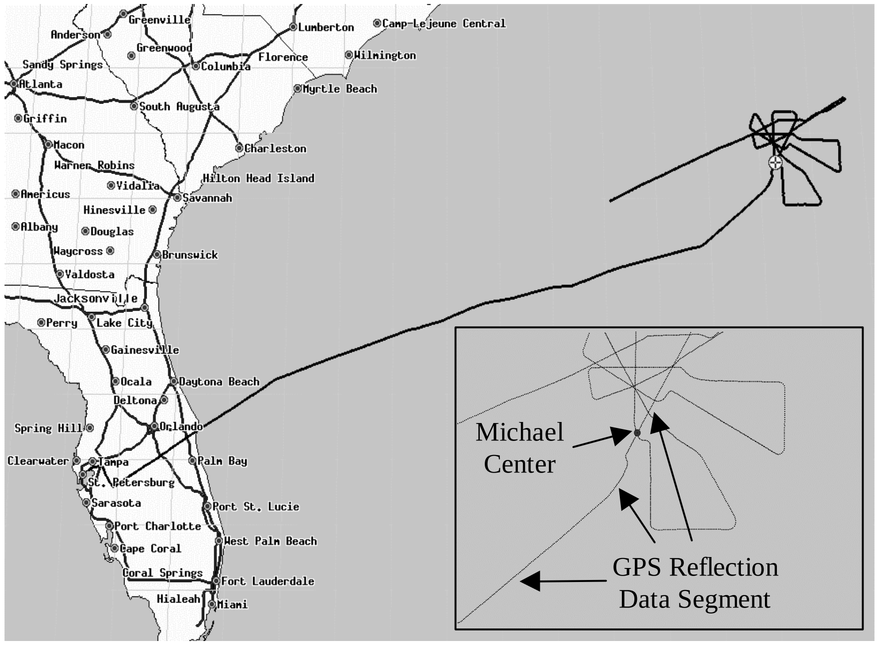
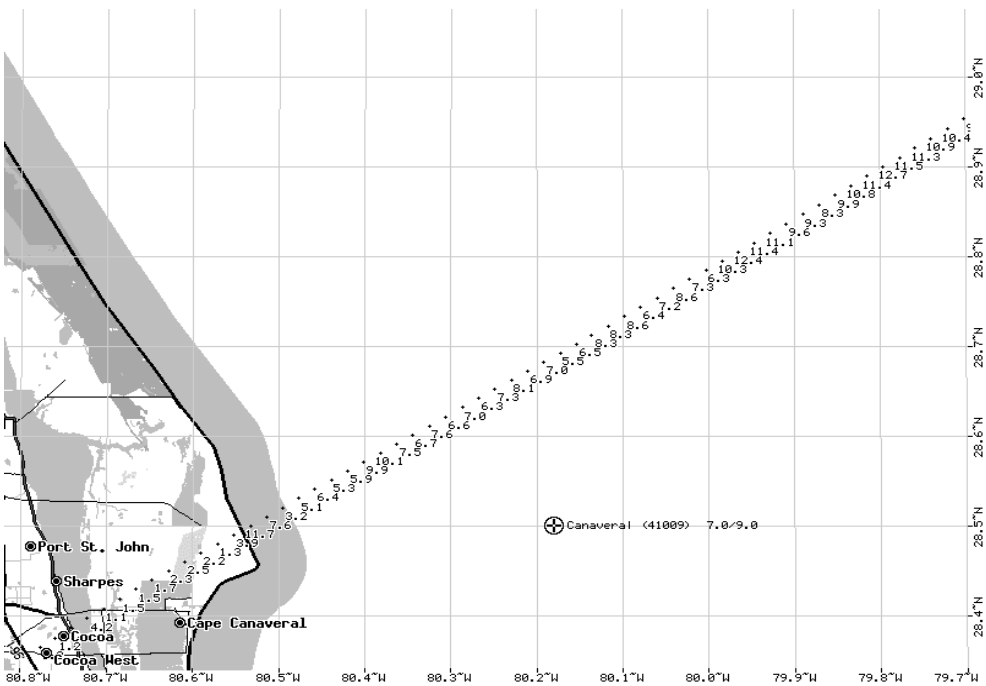
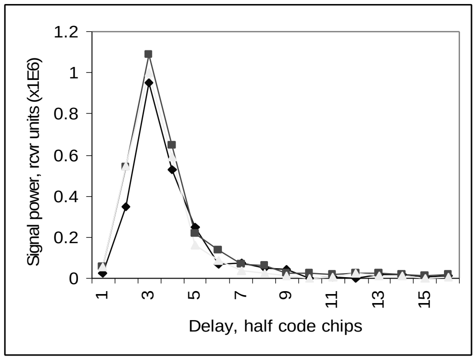


(a) Aircraft flight path on October 18, 2000



(b) Wind speed retrieval near Canaveral Buoy (41009) for satellite PRN 29

Figure 1.



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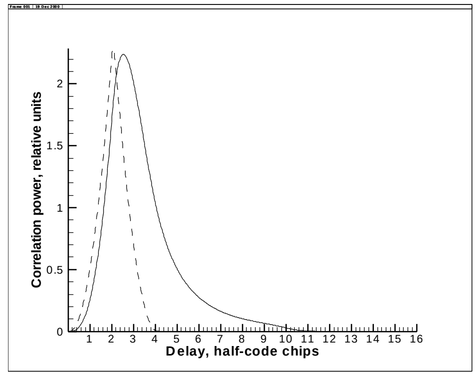

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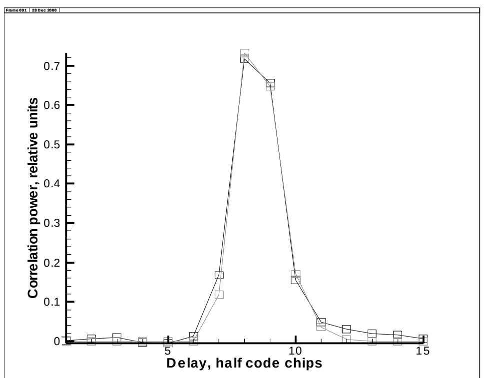
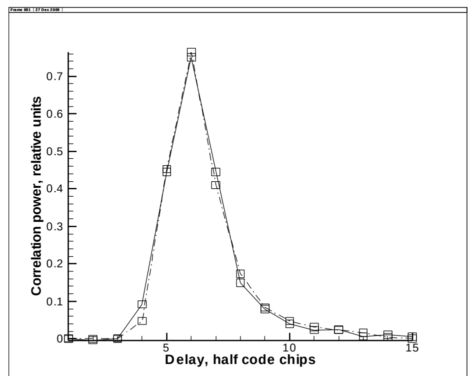
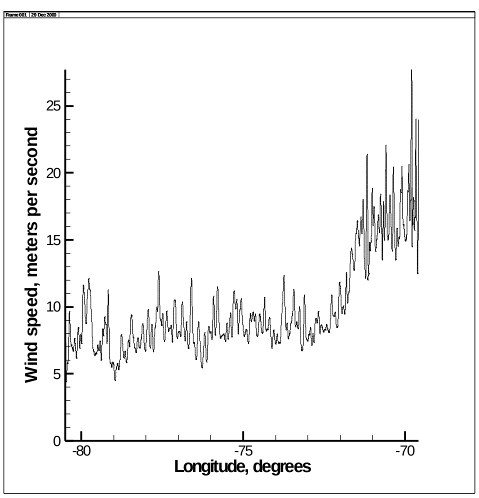


(c)



(d)

Figure 2. Panel (a) overlaid power vs. delay samples from PRN 21 inside the center of Michael. Panel (b) theoretical power vs. delay for 1- and 23-meters per second wind speed. Panels (c) and (d) are examples of matched filter selection of "best fit" to determine wind speed.



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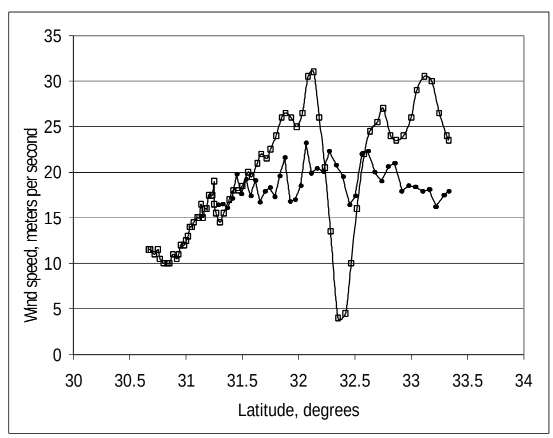

(b)

Figure 3. (a) Retrieval of entire flight track into Michael using PRN 29. Panel (b) is a composite of maximum, one-minute-averaged GPS derived wind speeds plotted with one minute samples from aircraft drift derived wind speeds. Aircraft data reaches minimum of approximately 5 m/s and maximum of 31 m/s.